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SUMMARY OF RESIDUAL STRESSES IN THE FUEL CHANNEL ROLLED JOINT

Report No. 90-46-K

D.H.B. Mok
Fracture Technology Section
Metallurgical Research Department

ABSTRACT

The knowledge of the residual stress field is required in the evaluation of flaws that are located in the rolled joint region. In this report, the residual stress measurements of low clearance rolled joint, over-extended, normal clearance, non-stress relieved rolled joint, over-extended, normal clearance, stress relieved rolled joint, normal clearance, stress relieved rolled joint and zero clearance rolled joint are presented in graphical forms. The thermal creep induced residual stress relaxation model proposed by AECL is also presented. The presented residual stress distributions should be updated when more data are available or when analytical confirmations are completed.

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83-270-551	826.241	October 1, 1990	90-46-K

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EXECUTIVE SUMMARY

SUMMARY OF RESIDUAL STRESSES IN THE FUEL CHANNEL ROLLED JOINT

D.H.B. Mok
Fracture Technology Section
Metallurgical Research Dept

In the construction of Pickering NGS-A, the tube expander was positioned incorrectly in the rolled joint assembly of some fuel channels. The tube expander over-extended beyond the start of the end fitting hub taper and caused expansion in the unsupported portion of the pressure tube. This over expansion induced high tensile residual stresses in the rolled joint region. In 1974 and 1975, a combination of the high residual stresses and a delayed hydride cracking mechanism caused cracking of some pressure tubes near the rolled joint regions in Pickering NGS-A, Units 3 and 4. As a result of these failures, extensive experimental programs were set up to measure the residual stress in the rolled joint region.

In this report, the available measured rolled joint residual stress distributions from the various experimental programs that are applicable to Ontario Hydro CANDU reactors (Pickering, Bruce and Darlington) are summarized in graphical form.

Based on the available data, the three major parameters that affect the residual stress distributions are the amount of over extension of the tube expander during rolling; the diametral clearance between the pressure tube and end fitting hub before rolling, and stress relieving after rolling. The rolling induced residual stresses are significant only in a localized region - usually within 30 to 40 mm inboard from the burnish mark. The type of roll joint with the highest residual stress is the over-extended, normal clearance, non-stress relieved rolled joint; and is followed by the low clearance rolled joint.

Under normal CANDU operating conditions, relaxation of residual stress induced by thermal creep is significant. The stress relaxation model proposed by AECL under predicts the residual stress relaxation under normal operating conditions.

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When performing flaw evaluations, rolled joint residual stresses should be considered if the flaw is located within 30 to 40 mm inboard from the burnish mark. The presented residual stress distributions can be used as a first approximation of the actual residual stress in a rolled joint. If a more detailed analysis is required, the presented residual stress distributions, along with the stress relaxation model proposed by AECL can be used to predict the current residual stress level. The database on rolled joint residual stresses is very limited for some types of rolled joints. When more data are available, this database should be updated. Furthermore, analytical confirmations such as finite element simulations of the rolling process, should be conducted to verify the residual stress measurements.

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SUMMARY OF RESIDUAL STRESSES IN THE FUEL CHANNEL ROLLED JOINT

1.0 INTRODUCTION

In 1974 and 1975, cracks in pressure tubes near the rolled joint regions were found in Pickering NGS-A, Units 3 and 4/1/. The cause of the cracks was identified as a combination of delayed hydride cracking and residual stresses resulting from the rolling operation. In some fuel channels, worn rolling tools (which was not known at the time) were used in the construction, which over-extended beyond the end fitting hub taper and caused expansion in unsupported portion of the pressure tube (see Figure 1.1). This over expansion of the pressure tube induced high tensile residual stresses in the rolled joint region. As a result of these rolled joint cracks, extensive experimental programs were set up to measure the residual stresses in the rolled joint region and to find solutions to rectify this problem in other CANDU reactors.

At the request of the Chemistry and Metallurgy Department of CPS, a survey was performed to collect the available data on rolled joint residual stresses. In this report, the available results from the various experimental programs that are applicable to Ontario Hydro CANDU reactors (Pickering, Bruce and Darlington) and actual measurements from pressure tubes removed from reactors are summarized.

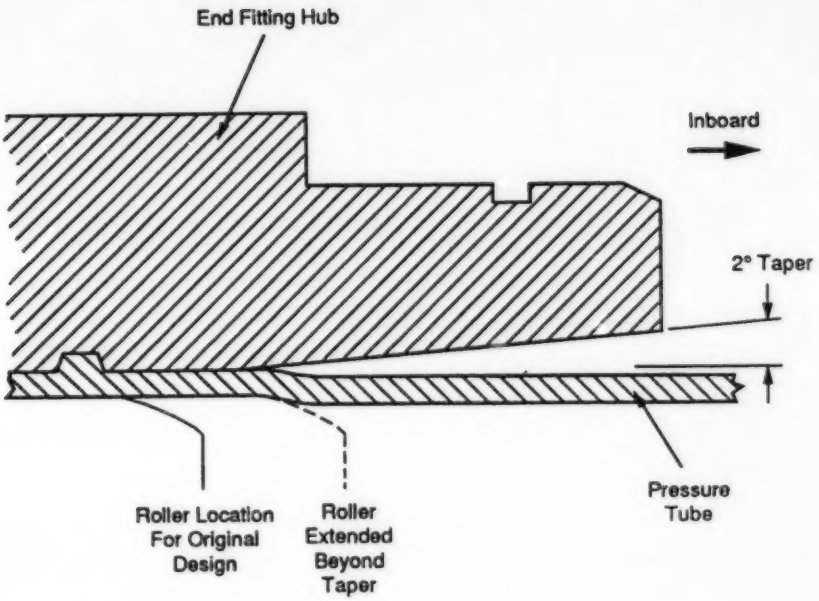

FIGURE 1.1- Schematic of Normal and Over-Extended Rolled Joints

2.0 CONCLUSIONS

a) The three major parameters that affect the pre-service residual stress distributions are the amount of over-extension, the diametral clearance between the pressure tube and end fitting hub before rolling, and stress relieving after rolling.

b) Rolling-induced residual stresses are significant only in a localized region, usually within 30 to 40 mm in-board from the burnish mark.

c) The type of rolled joint with the highest residual stresses is the over-extended normal clearance, non-stress relieved rolled joints. This is followed by the low clearance rolled joints.

d) Significant relaxation of the residual stresses occurs during initial commissioning and under normal operating conditions.

e) The stress relaxation model proposed by AECL under predicts residual stress relaxation under normal operating condition.

3.0 RECOMMENDATIONS

a) Rolled joint residual stresses should be considered in a flaw evaluation if the flaw is located within 30 to 40 mm in-board from the burnish mark.

b) The residual stress distributions presented in this report can be used as a first approximation of the actual residual stress in an existing fuel channel, especially if the data is from a removed tube which accounts for stress relaxation under normal operating condition.

c) The stress relaxation model proposed by AECL can be used to predict relaxation of rolled joint residual stresses.

d) The existing database in this report on rolled joint residual stress should be updated when more data are available.

e) Analytical confirmations such as finite element simulations of the rolling process should be conducted to verify the residual stress measurements.

4.0 DEFINITIONS OF TERMINOLOGY

The terminologies used to describe the different types of rolled joints in this report are extracted from the "Fuel Channel Design and Operating Parameters" guideline provided by AECL/2/.

4.1 Normal Clearance

The diametral clearance between pressure tube and end fitting bore is between 0.18 and 0.53 mm before rolling.

4.2 Low Clearance

The diametral clearance between pressure tube and end fitting bore is between 0.13 and 0.25 mm before rolling.

4.3 Zero Clearance

The diametral clearance between pressure tube and end fitting bore is between -0.18 mm (interference fit) and 0.05 mm before rolling.

4.4 Stress Relieved

The rolled joint is heat treated to relieve the high residual stresses produced by the rolling operation.

4.5 Over-extended

The tube expander (rolling tool) is inserted too far in-board beyond the start of the end fitting hub taper.

5.0 ROLLED JOINTS IN ONTARIO HYDRO CANDU REACTORS

At the time of the rolled joint crackings in Pickering NGS-A, Units 3 and 4, other Ontario Hydro nuclear generating stations were at different stages of planning and completion. Therefore, some generating stations have rolled joint designs such as the zero clearance joints that produce very low residual stresses. For other stations a heat treating process was used to relieve the high residual stresses in joints that had already been rolled. The different types of rolled joints currently in use in Ontario Hydro CANDU reactors are summarized in Table 5.1/2/.

TABLE 5.1

Rolled Joints in Ontario Hydro CANDU Reactors

Station	Unit	Rolled Joint Type
Pickering NGS-A	1, 2, 3*	Low Clearance
Pickering NGS-A	4	Over-extended, Normal Clearance
Pickering NGS-B	5, 6, 7, 8	Zero Clearance
Bruce NGS-A	1, 2	Over-extended, Normal Clearance, Stress Relieved
Bruce NGS-A	3, 4	Normal Clearance, Stress Relieved
Bruce NGS-B	5, 6, 7, 8	Zero Clearance
Darlington NGS-A	1, 2, 3, 4	Zero Clearance

* after retubing

6.0 RESIDUAL STRESS DISTRIBUTIONS IN ROLLED JOINT REGION

Due to the variability of the rolling process, the residual stress distributions in the rolled joint region are different from tube to tube. However, the residual stress distributions of the same rolled joint type are similar in general. After the pressure tube cracking in Pickering NGS-A, Unit 3, AECL, CGE, Orenda and OHRD conducted experimental programs to measure the residual stresses in the rolled joint region and to develop a procedure to reduce the level of residual stresses in future CANDU reactor designs. The results summarized here are extracted from the reports of the various research programs.

As mentioned in Section 5, different types of rolled joints are used in different Ontario Hydro CANDU reactors. The residual stress distributions for each type of

rolled joint are presented separately. The presented data are summarized in Table 6.1. The rolled joint identifications used in this report are the same as those in the references. The in-reactor life for these rolled joints are measured in the equivalent full power hour (EFPH). Therefore, 0 EFPH means beginning of life, i.e., the rolled joint is in the as-rolled or as stress relieved condition, before the commissioning of the unit. If the measurement was performed on a rolled joint that was removed from service, the residual stress distributions are indicated by an asterisk (*) in the figures and in Table 6.1.

If the data were available, the hoop and axial residual stress distribution along the inside and outside tube surfaces are presented. The reference axial (zero) location is at the burnish mark and distance along the pressure tube is positive in-board. For some measurements, the burnish mark location was unknown and an over-extension of 12.7 mm was assumed. These results are indicated by a dagger (†) in the figures.

All the results presented in this report are from strain gauge measurements. According to Turner/6/, the error on the measurement is +/- 35 MPa.

6.1 Low Clearance Rolled Joint

Experiments showed that low clearance rolled joints have relatively small residual stress. All reactors which have undergone the Large Scale Fuel Channel Replacement program use this type of rolled joint/2/. Currently, these reactors are Pickering NGS-A, Units 1 and 2 and Pickering NGS-A, Unit 3 (currently underway).

Specific measurements of residual stress were not made for this type of rolled joint. The residual stress distributions for rolled joints with similar diametral clearance are found in/3/. The axial and hoop residual stress distributions along the inside surface are shown in Figures 6.1 and 6.2 respectively. Both the axial and hoop residual stresses decrease to zero away from the rolled joint transition region. The maximum hoop residual stress is about 200 MPa and is located at about 5 to 10 mm in-board from the burnish mark.

6.2 Over-extended, Normal Clearance, Non-stress Relieved Rolled Joint

The over-extended, normal clearance, non-stress relieved rolled joint produces the highest rolling residual stresses. Pickering NGS-A, Unit 4 is currently the only nuclear generating station that has this type of rolled joint. The average roller over-extension is about 19.1 mm in the west end rolled joints and about 8.9 mm in the east end rolled joints/15/.

The residual stress distributions for both the axial and hoop directions along the inside and outside surfaces are extracted from /4, 5, 6, 7 and 8/ and are presented in Figures 6.3 to 6.6. Although the measurements have significant scatter, the results show similar trends. Furthermore, the residual stresses for rolled joints removed from service are significantly lower than those in the as rolled condition.

6.3 Over-extended, Normal Clearance, Stress Relieved Rolled Joint

Before the discovery of the rolled joint cracking problem in Pickering NGS-A, Unit 3, the pressure tube and end fitting assemblies had already been rolled in Bruce NGS-A, Units 1 and 2. These rolled joints were also over-extended. To avoid a similar cracking problem, a heat treating process (530°C for 30 minutes/9/) was performed to relieve the high residual stresses.

The stress relieving operation was apparently too late for some fuel channels. In 1982, a leak developed in fuel channel B2-X14 and the pressure tube was removed/5/. The residual stress in this channel was measured. The results showed that the stress relieving operation was performed correctly. This indicated that the crack was initiated before the stress relieving operation. Similar leaking cracks were also found in fuel channels B2-A14/10/ and B2-N06/11/.

Typical residual stress distributions for stress relieved, over-extended rolled joint are shown in Figures 6.7 to 6.10/4, 5, 10 and 11/. The maximum residual stresses in both axial and hoop directions are less than 100 MPa and are much lower than non-stress relieved, over-extended rolled joints as those depicted in Figures 6.3 to 6.6. The residual stress distributions from removed tubes show some stress relaxation which is most likely due to thermal creep.

6.4 Normal Clearance, Stress Relieved Rolled Joint

After the discovery of rolled joint cracking problem in Pickering NGS-A, Unit 3, the construction of Bruce NGS-A, Units 3 and 4 used a new rolling procedure to ensure that over-extension would not occur. Furthermore, the heat treating process used in Bruce NGS-A, Units 1 and 2 was also performed to further reduce the level of residual stresses.

The residual stress distributions for this type of rolled joint are shown in Figures 6.11 to 6.14/12/. Although only one set of data is shown in these figures, the distributions shown are for a rolled joint produced under extreme rolling and stress relieved condition (large diametral clearance). Therefore, the distributions should be conservative. The maximum residual hoop stress on the inside surface is about 230 MPa located about 6 to 7 mm from the burnish mark.

6.5 Zero Clearance Rolled Joint

One of the major parameters that controls the residual stress magnitude is the diametral clearance between the pressure tube and the end-fitting hub. The experiments showed that a rolled joint with a very small diametral clearance or interference has very low tensile hoop stress. Therefore, the more recent generating stations, Pickering NGS-B, Bruce NGS-B, and Darlington NGS-A, have zero clearance rolled joints in their designs/2/.

The axial and hoop residual stress distributions along the inside and outside surfaces are summarized in Figures 6.15 to 6.18/13/. The twelve sets of data shown

have a large range of scatter. The maximum tensile hoop stress on the inside surface is about 100 MPa and is located in the supported region of the pressure tube.

6.6 Stress Relaxation Under Normal Operating Conditions

The residual stress distributions presented above are either in the as-rolled condition or in the stress relieved condition, i.e., before the commissioning of the unit. The experimental results showed that after the standard commissioning procedure (300 hours at 250°C), a decrease of about 20% of the residual stress would be expected/14/. A further 15 to 20% decrease could be expected after 1000 hours of operation and a slow decrease thereafter. If the initial residual stress was low as in the zero clearance rolled joints, very little stress relaxation would be expected.

A stress relaxation model for Zr-2.5wt% Nb pressure tubes for Pickering NGS-A, Unit 3 and 4 operating conditions, was proposed by AECL-CRNL/15/. The stress relaxation prediction as a function of time is presented in Figure 6.19. Because the inlet and outlet temperatures are different, the rate of stress relaxation is different with faster rate for the outlet end. The values identifying the curves in this figure are the initial residual stress values (in ksi). The residual stresses for two rolled joint removed from Pickering NGS-A, Unit 3 are also included in Figure 6.19 for comparison/16/. The comparison shows that the predictions over-estimated the final residual stresses. The difference is about 50 MPa which is within the range of measurement and calculation errors. Although the stress relaxation model was originally proposed for Pickering NGS-A, Unit 3 and 4, but other CANDU reactors are operating at either the same or higher temperatures, which would have faster relaxation rate. Therefore, this stress relaxation model can be used to estimate the residual stresses for all other CANDU reactors.

TABLE 6.1

Summary of Presented Rolled Joint Data

Rolled Joint Identification	Reference	In-Reactor Life (EFPH)
ZC-16	3	0
ZC-18	3	0
PC-24	4	0
B2K02W	4	0
B2Y12E	5	0
B2Y12W	5	0
P3G04W*	6	0
P3G12W*	6	0
P3J03E*	6	0
P3J08E*	6	0
P4K11W*	6	0
P4K22W*	6	0
P3F13W*	7	91100
P3J09E*	8	83700
B2J01W	4	0
B2X14E*	5	31200
B2A14E*	10	35700
B2N06W*	11	58100
SR-46	12	0
PB-1 TOP	13	0
PB-1 BOT	13	0
PB-2 TOP	13	0
PB-2 BOT	13	0
PB-3 TOP	13	0
PB-3 BOT	13	0
PB-4 TOP	13	0
PB-4 BOT	13	0
PB-9 TOP	13	0
PB-9 BOT	13	0
PB-10 TOP	13	0
PB-10 BOT	13	0

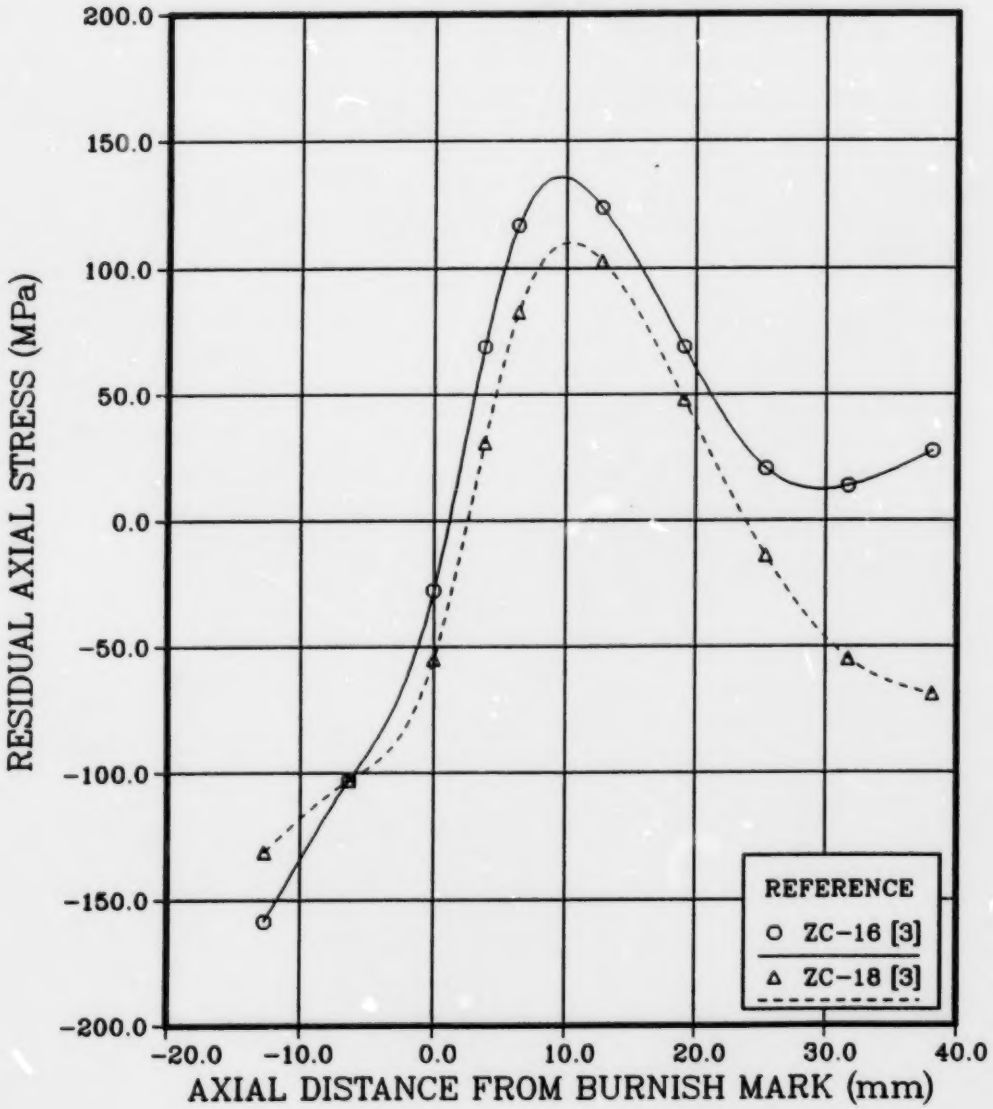

FIGURE 6-1- Residual Axial Stress Distribution Along the Inside Surface for Low Clearance Rolled Joints

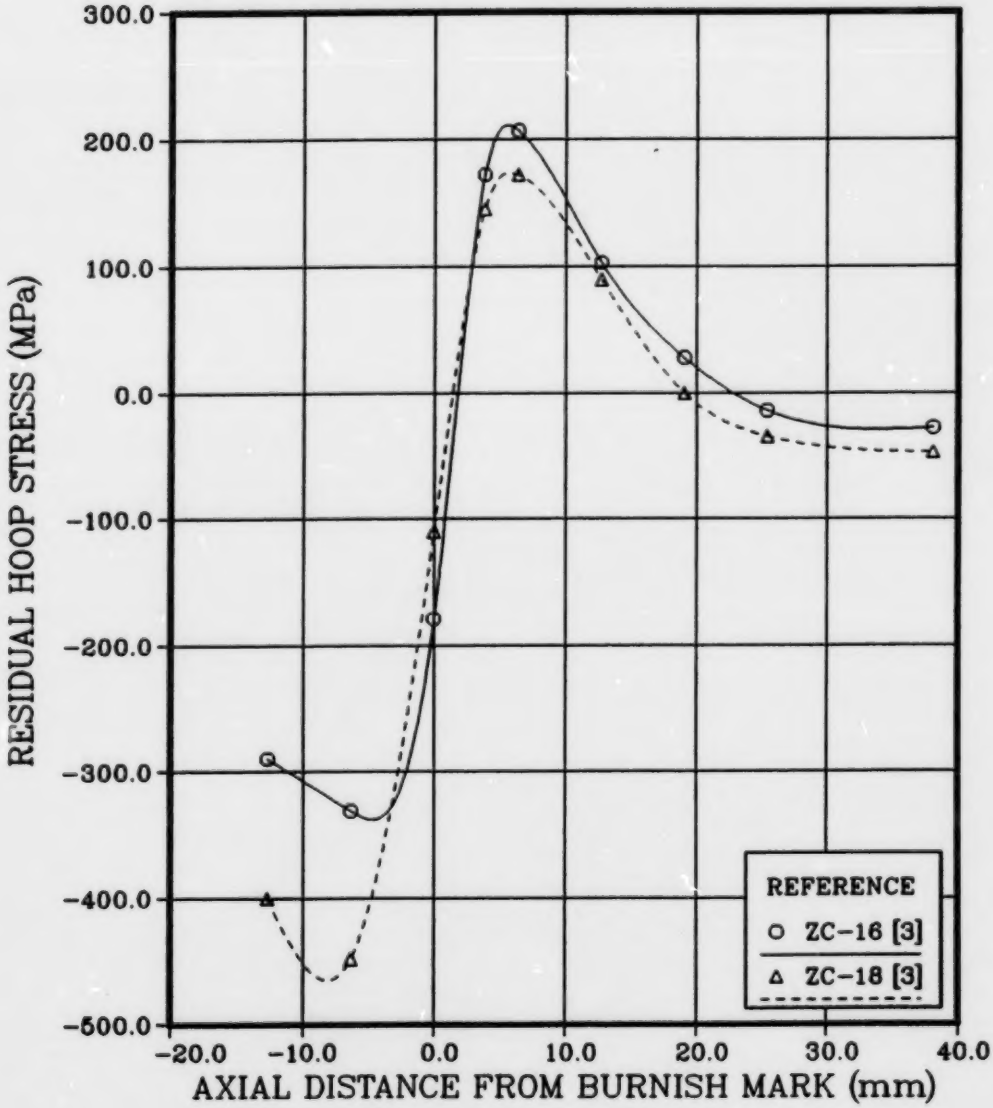

FIGURE 6.2 - Residual Hoop Stress Distribution Along the Inside Surface for Low Clearance Rolled Joints

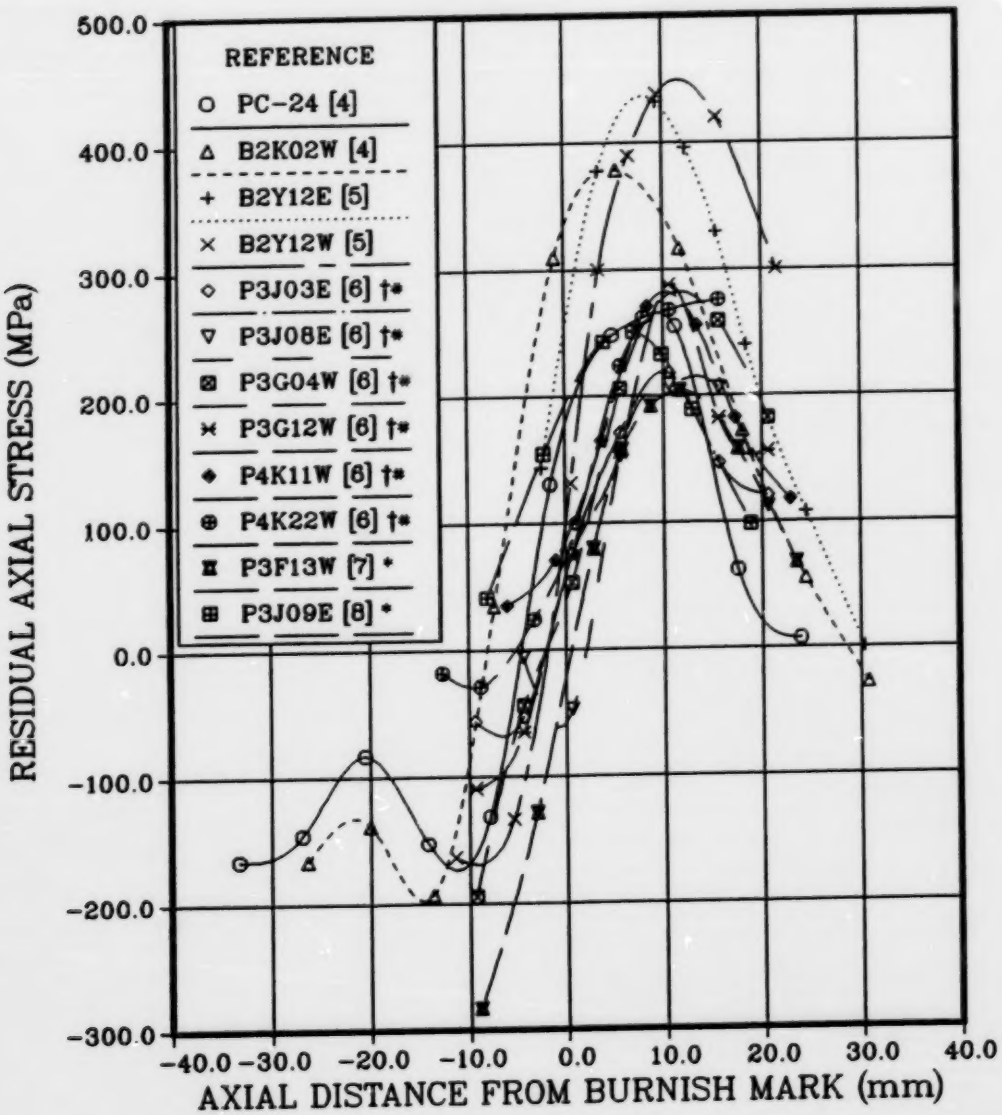

FIGURE 6.3 - Residual Axial Stress Distribution Along the Inside Surface for Over-Extended, Normal Clearance, Non-stress Relieved Rolled Joints

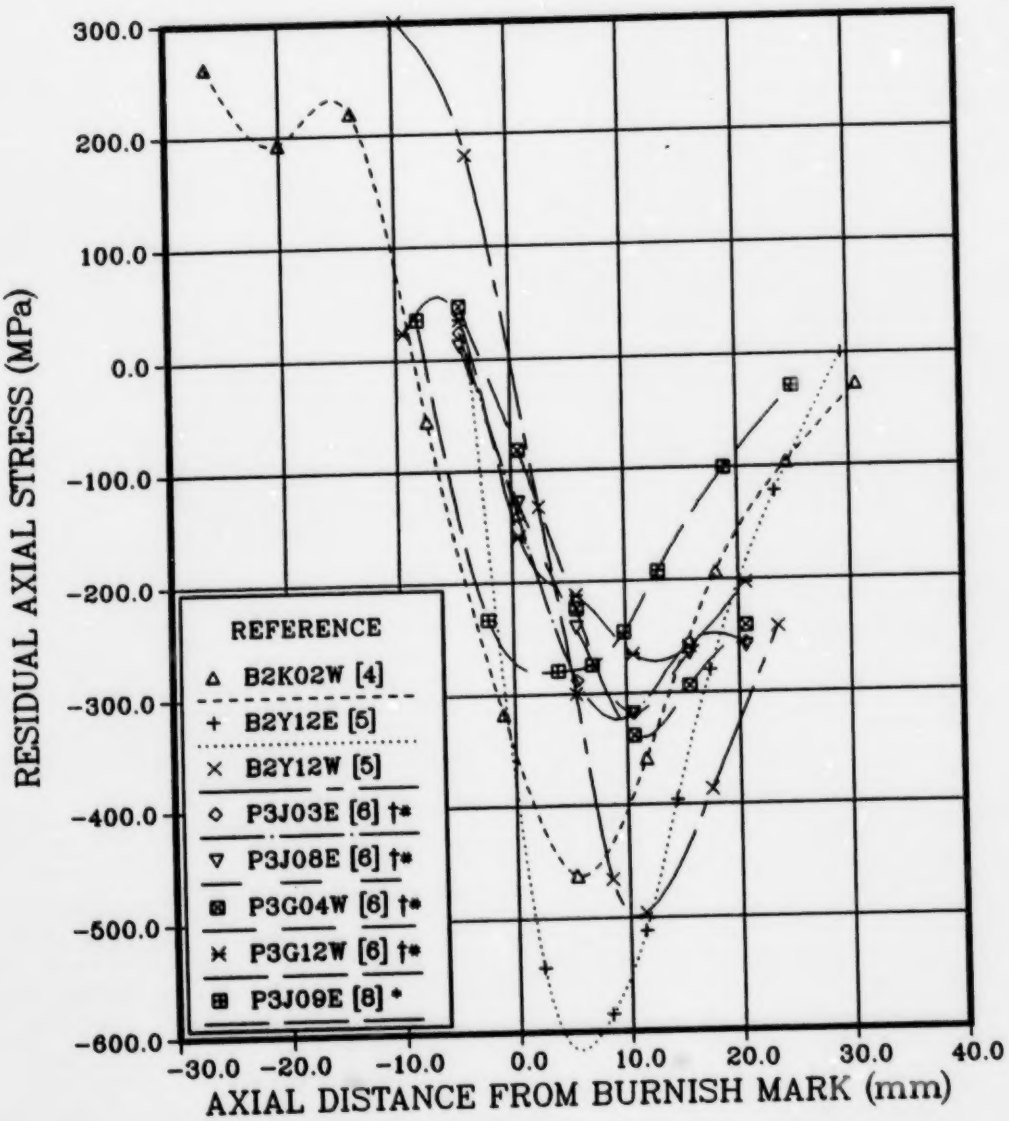

FIGURE 6.4 - Residual Axial Stress Distribution Along the Outside Surface for Over-Extended, Normal Clearance, Non-stress Relieved Rolled Joints

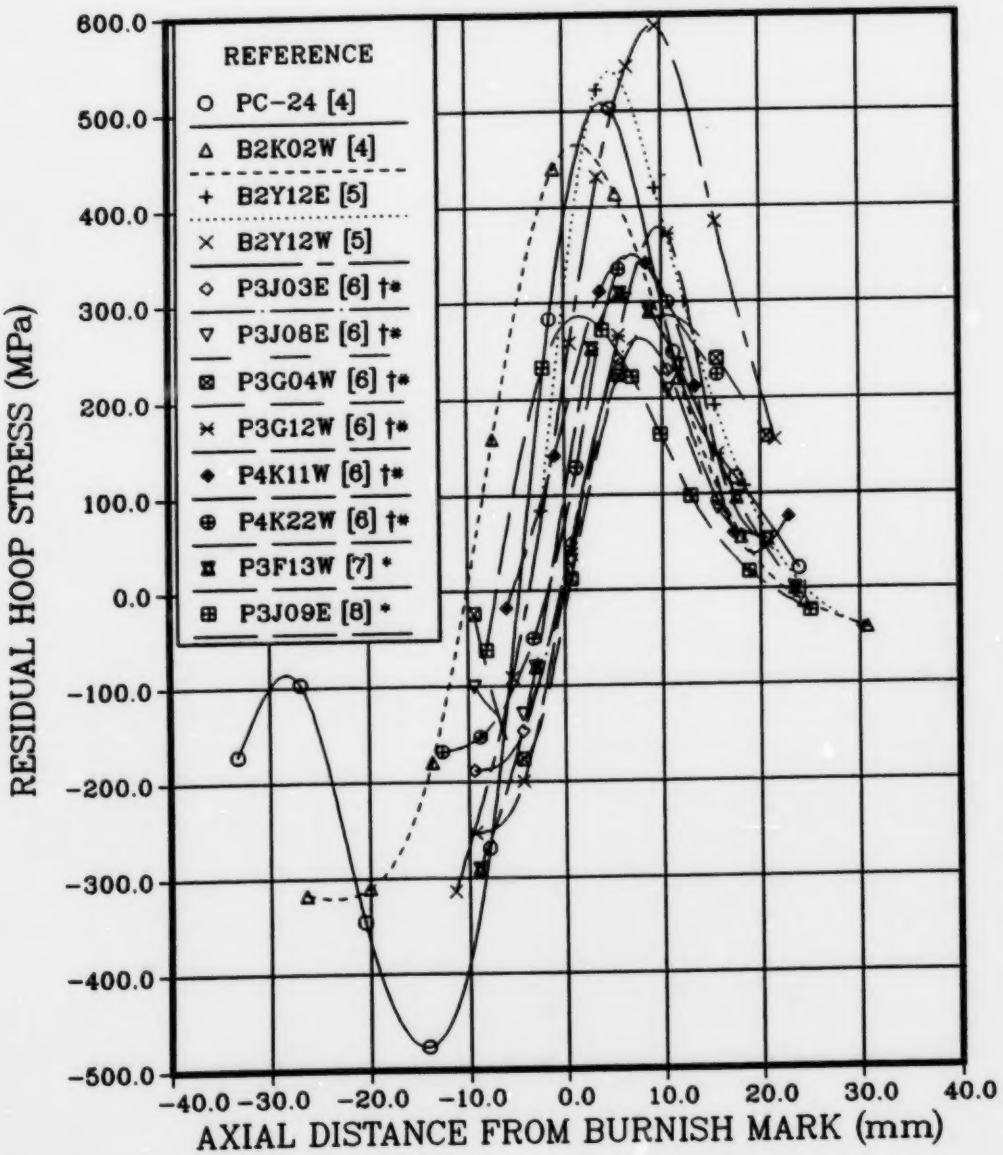

FIGURE 6.5 - Residual Hoop Stress Distribution Along the Inside Surface for Over-Extended, Normal Clearance, Non-stress Relieved Rolled Joints

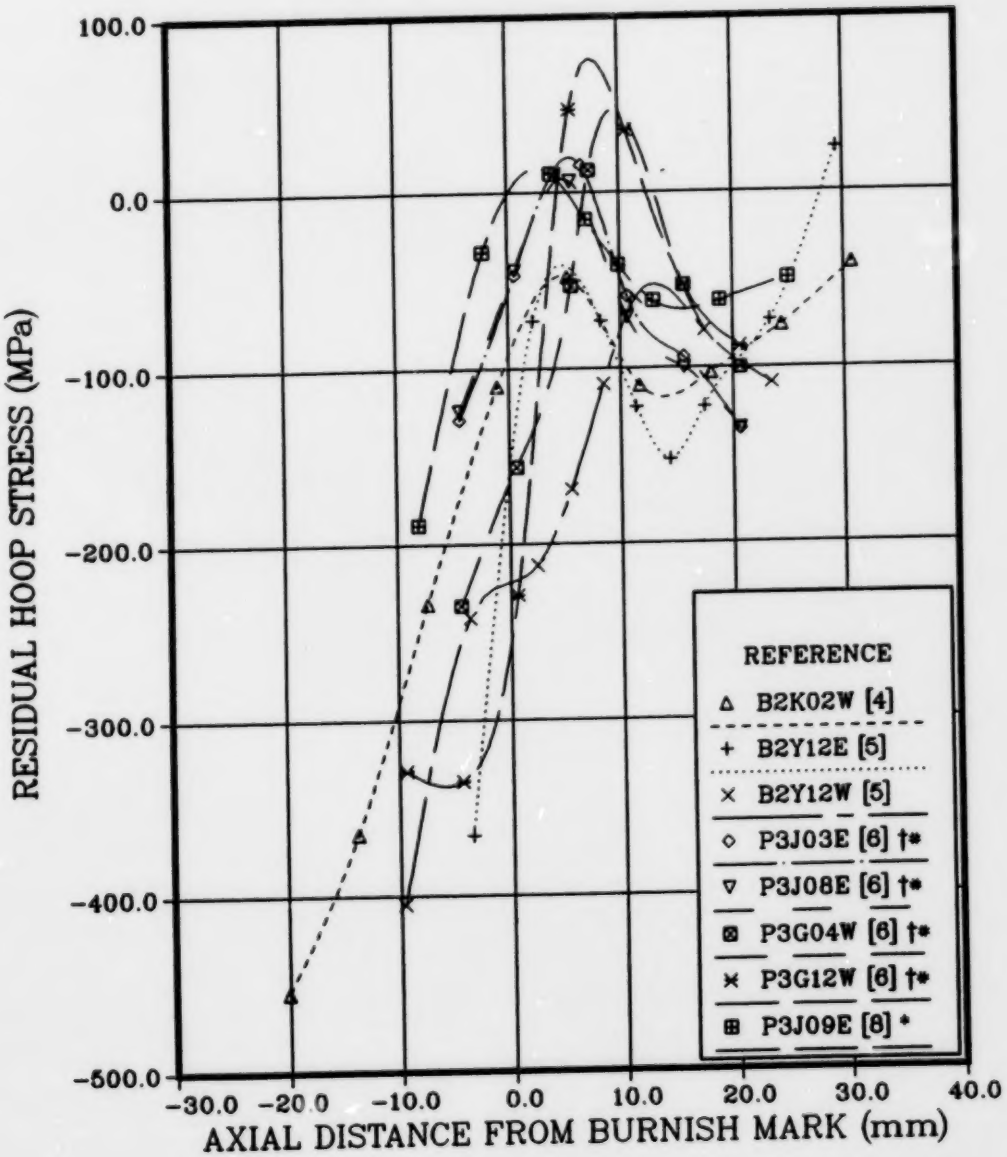

FIGURE 6.6 - Residual Hoop Stress Distribution Along the Outside Surface for Over-Extended, Normal Clearance, Non-stress Relieved Rolled Joints

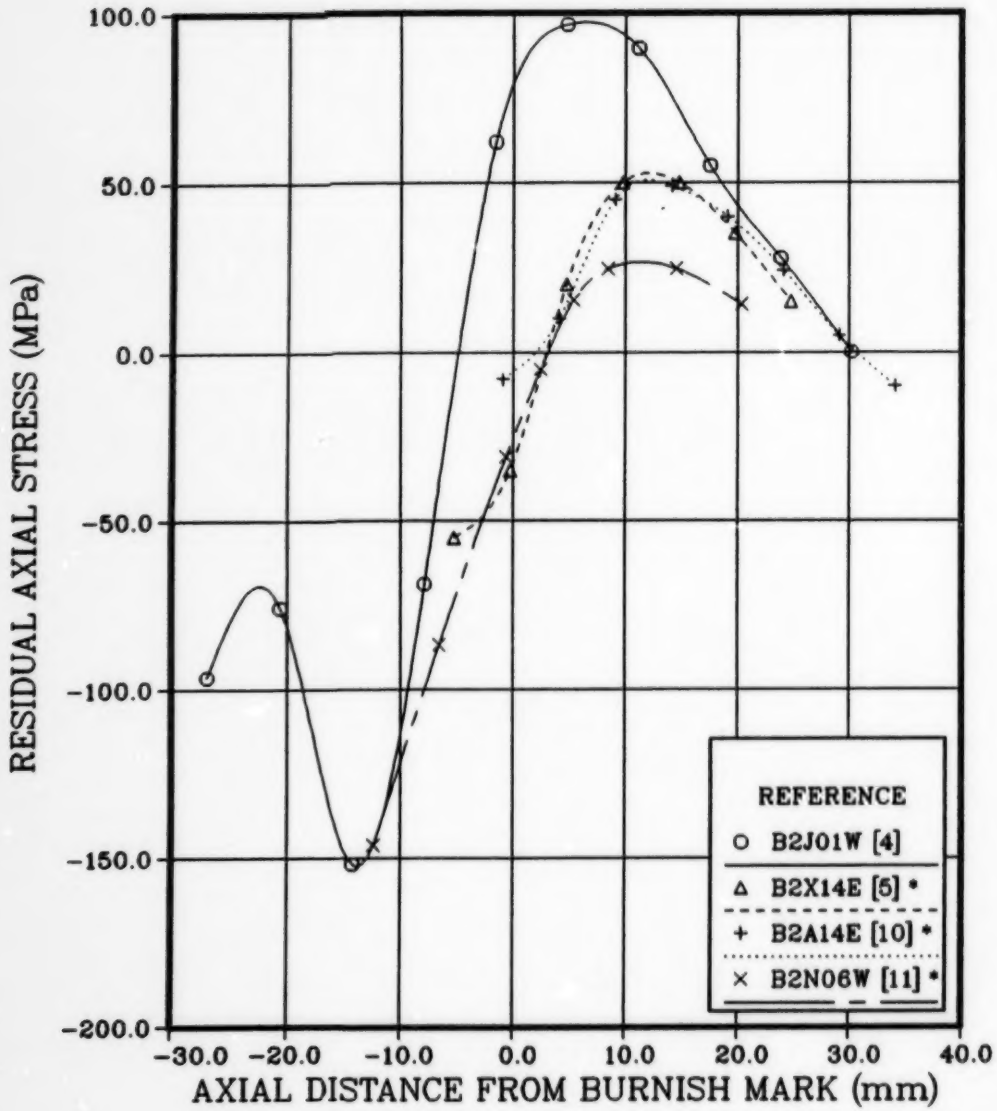

FIGURE 6.7 - Residual Axial Stress Distribution Along the Inside Surface for Over-Extended, Normal Clearance, Stress Relieved Rolled Joints

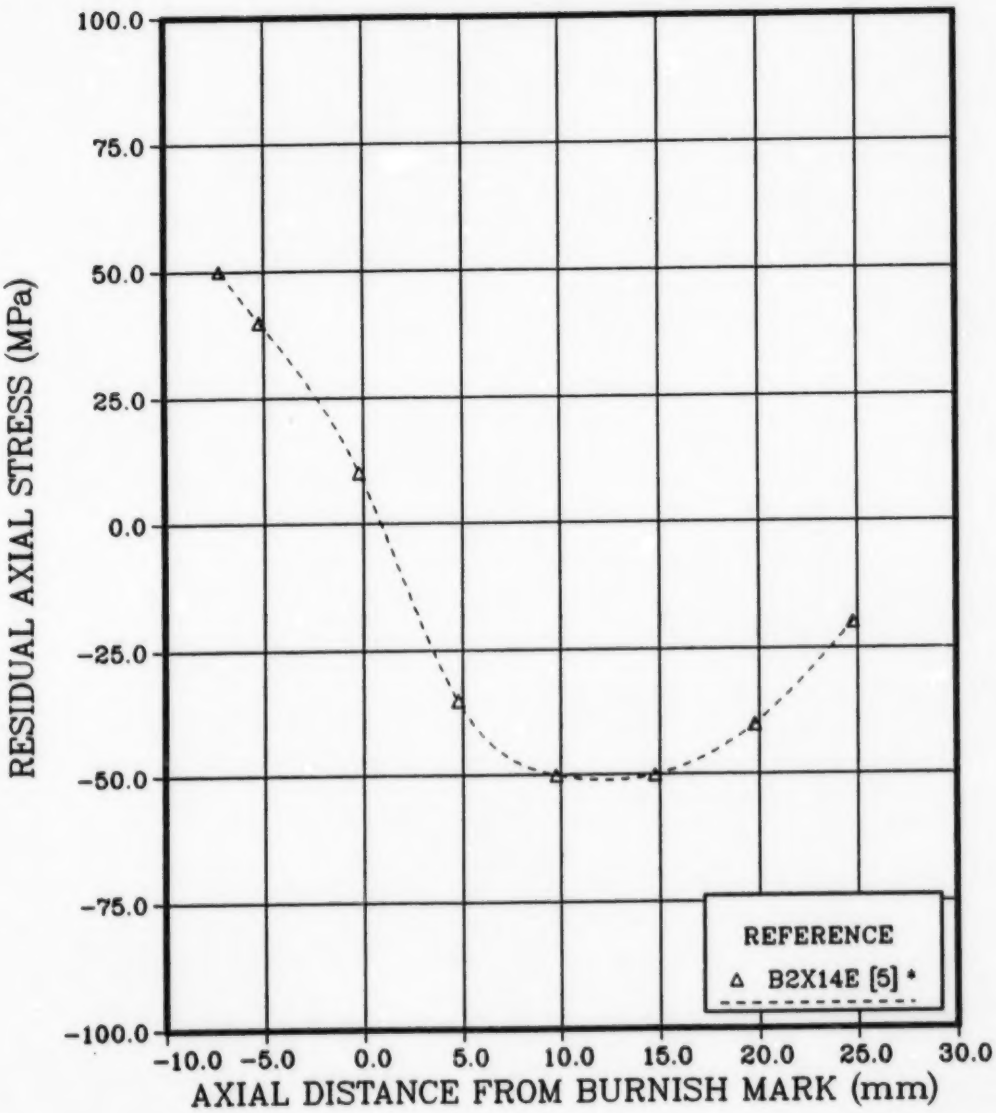

FIGURE 6.8 - Residual Axial Stress Distribution Along the Outside Surface for Over-Extended, Normal Clearance, Stress Relieved Rolled Joints

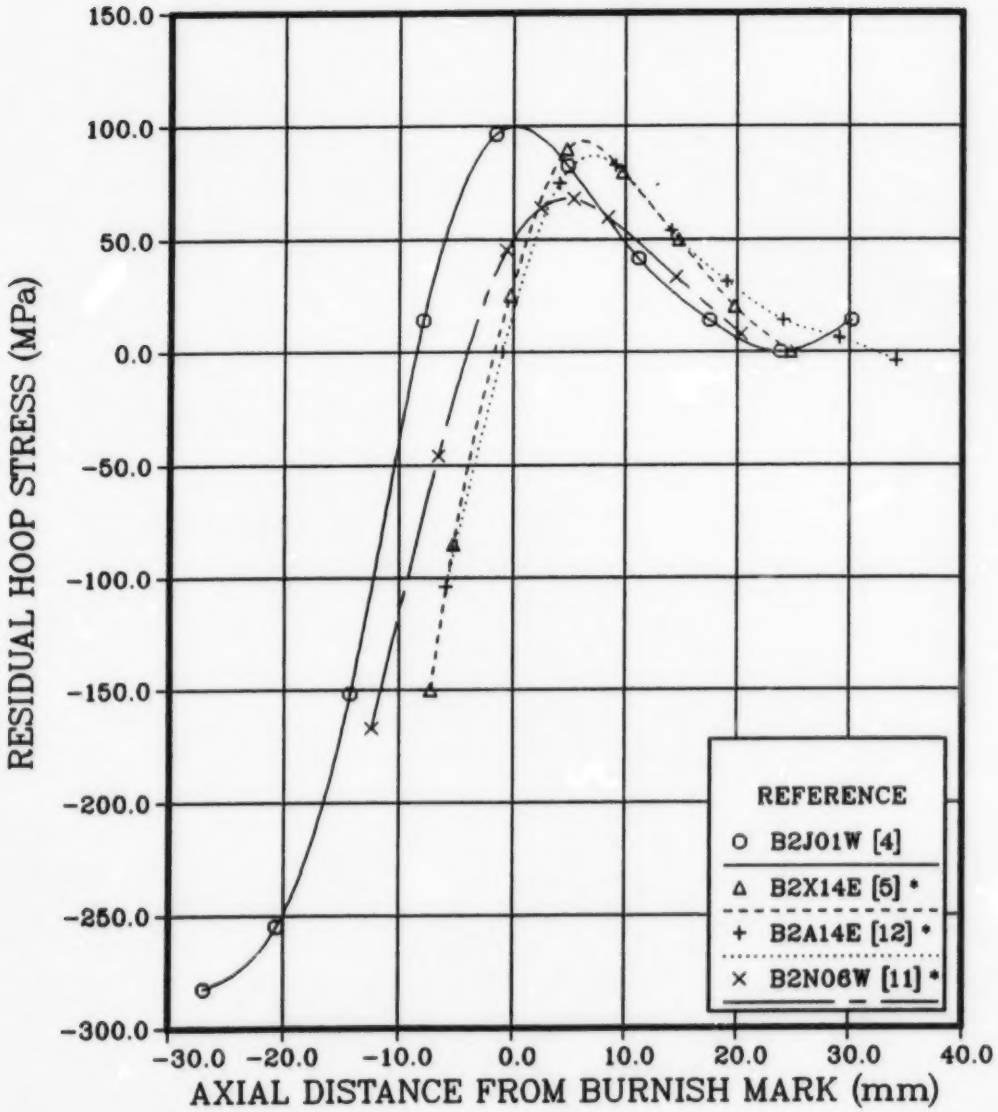

FIGURE 6.9 - Residual Hoop Stress Distribution Along the Inside Surface for Over-Extended, Normal Clearance, Stress Relieved Rolled Joints

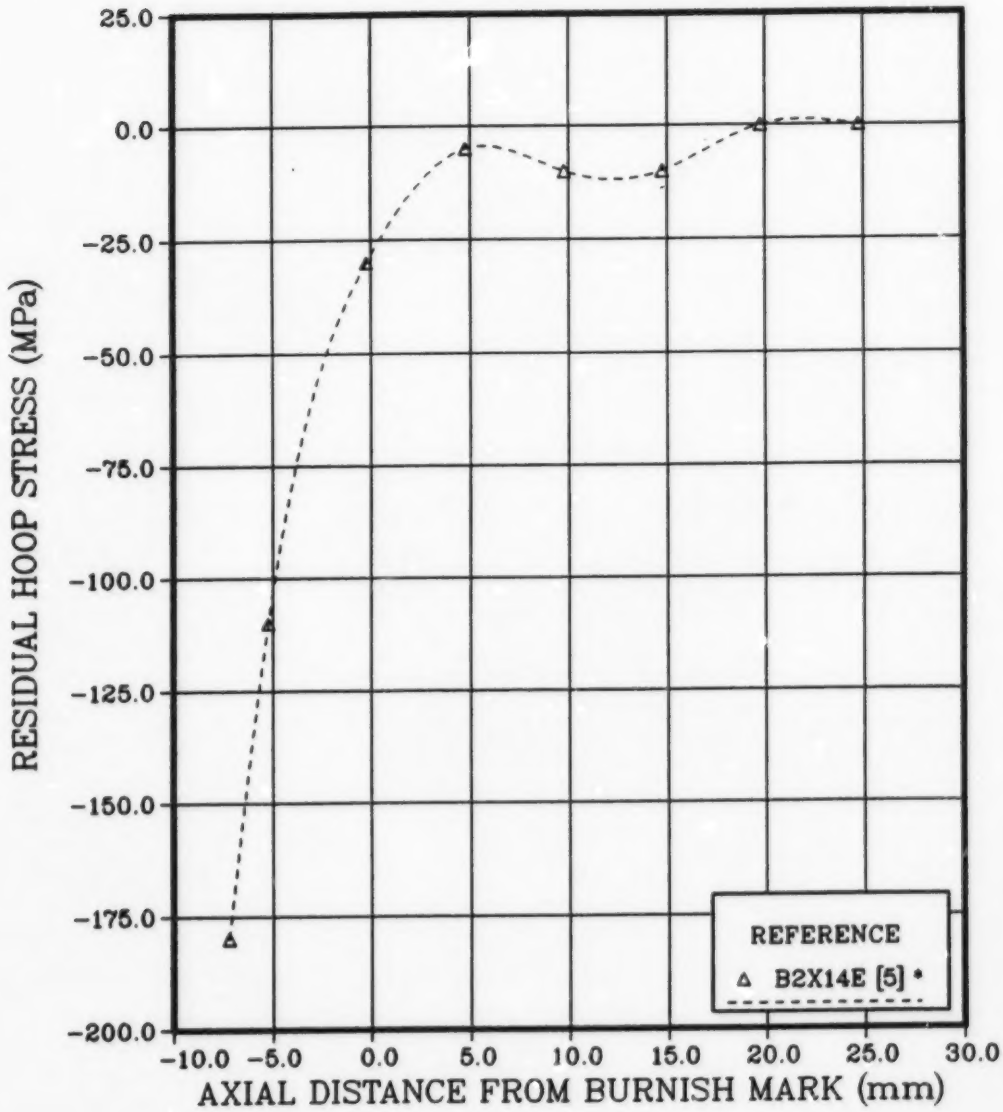

FIGURE 6.10 - Residual Hoop Stress Distribution Along the Outside Surface for Over-Extended, Normal Clearance, Stress Relieved Rolled Joints

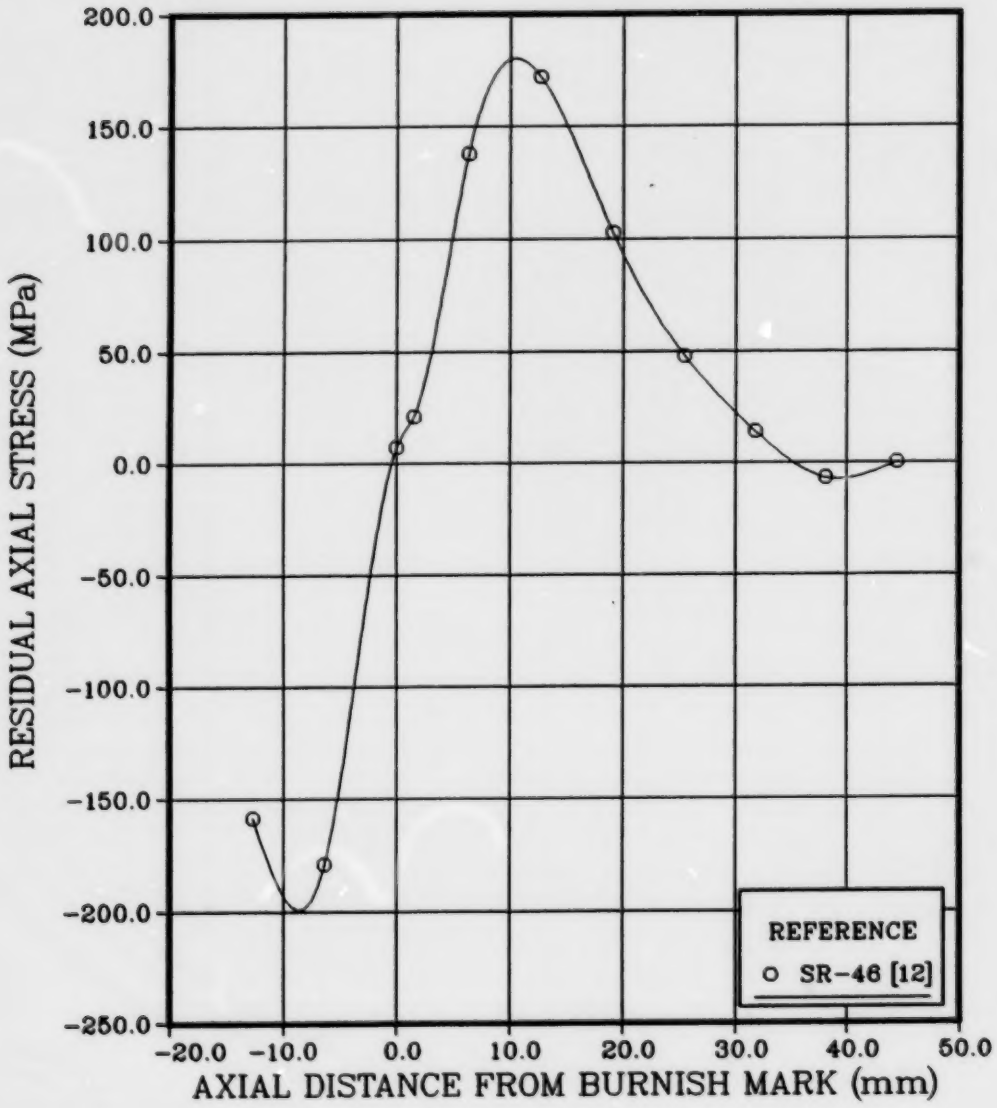

FIGURE 6.11 - Residual Axial Stress Distribution Along the Inside Surface for Normal Clearance, Stress Relieved Rolled Joints

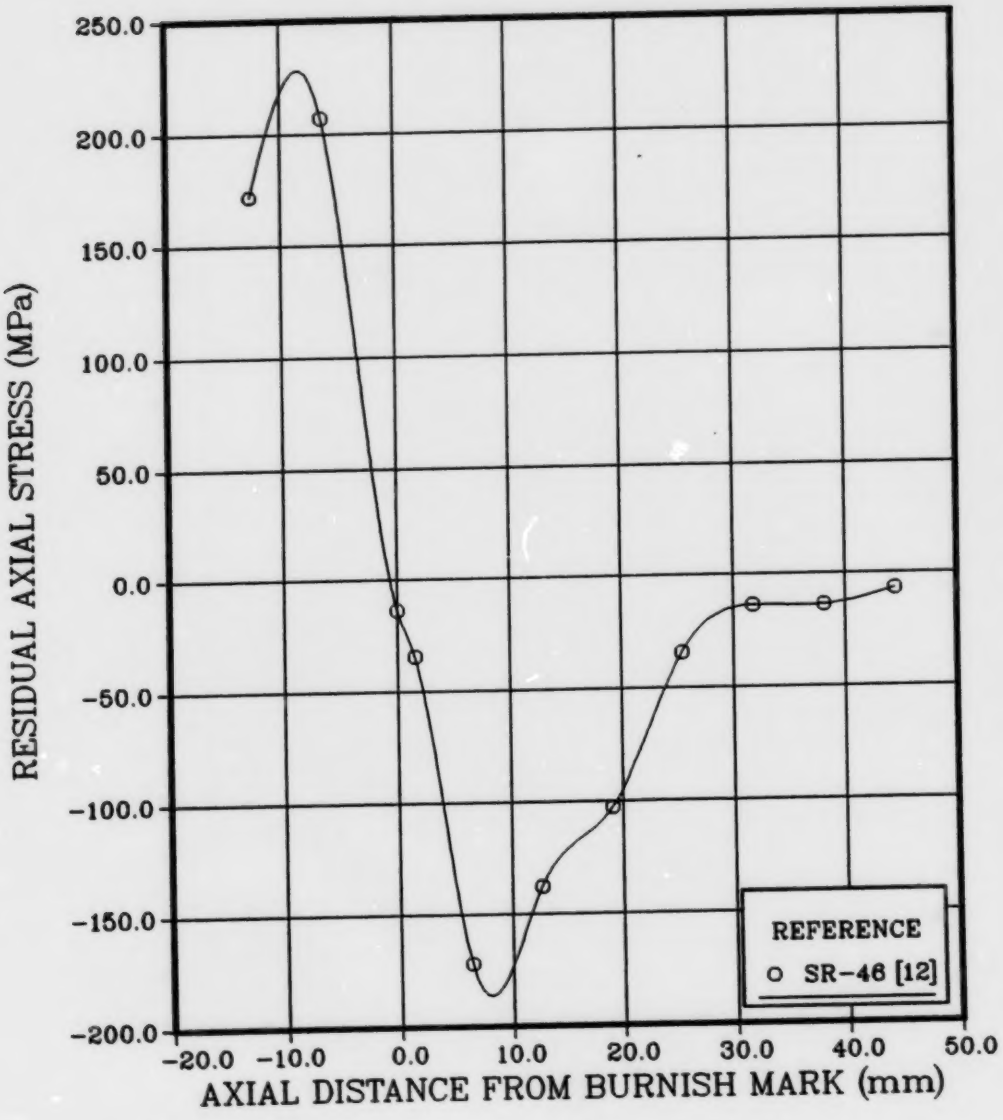

FIGURE 6.12 - Residual Axial Stress Distribution Along the Outside Surface for Normal Clearance, Stress Relieved Rolled Joints

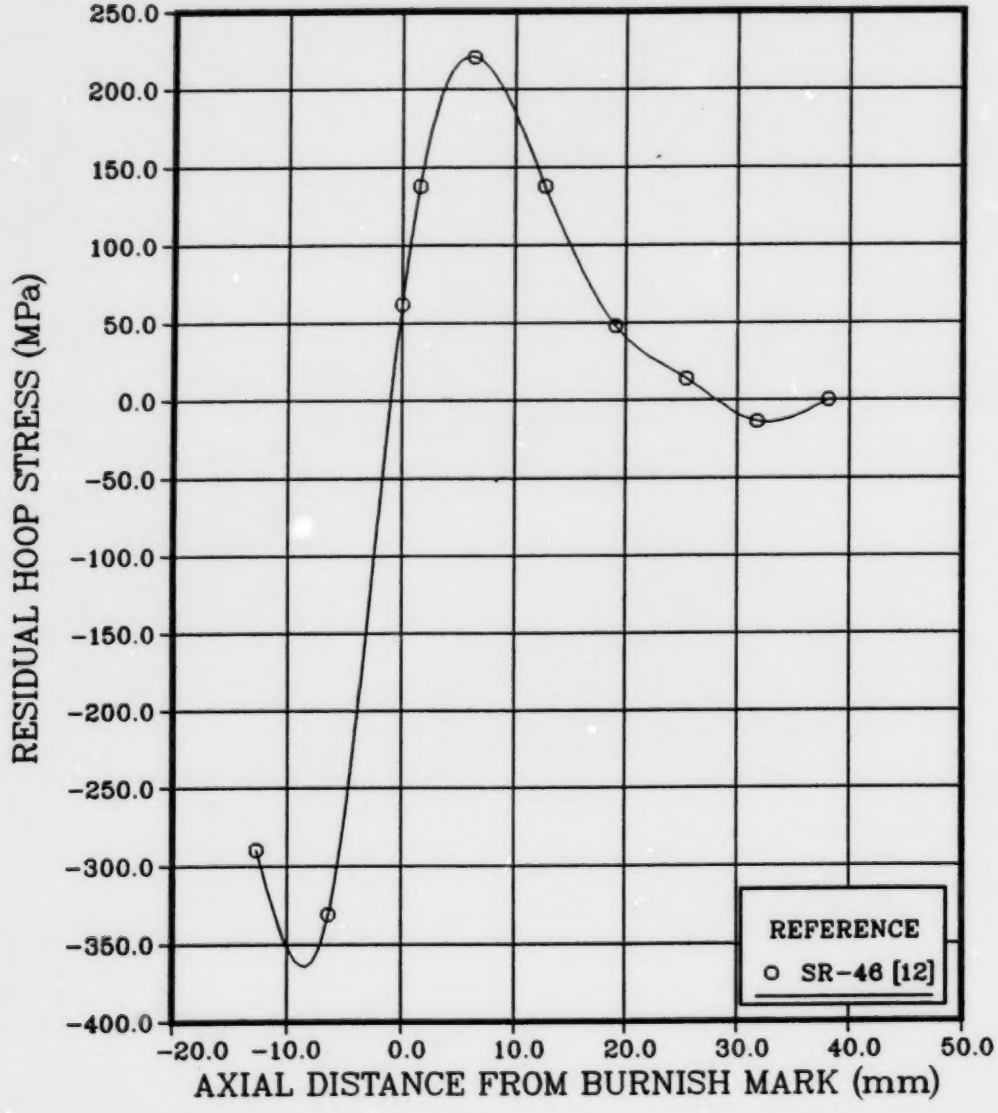

FIGURE 6.13 - Residual Hoop Stress Distribution Along the Inside Surface for Normal Clearance, Stress Relieved Rolled Joints

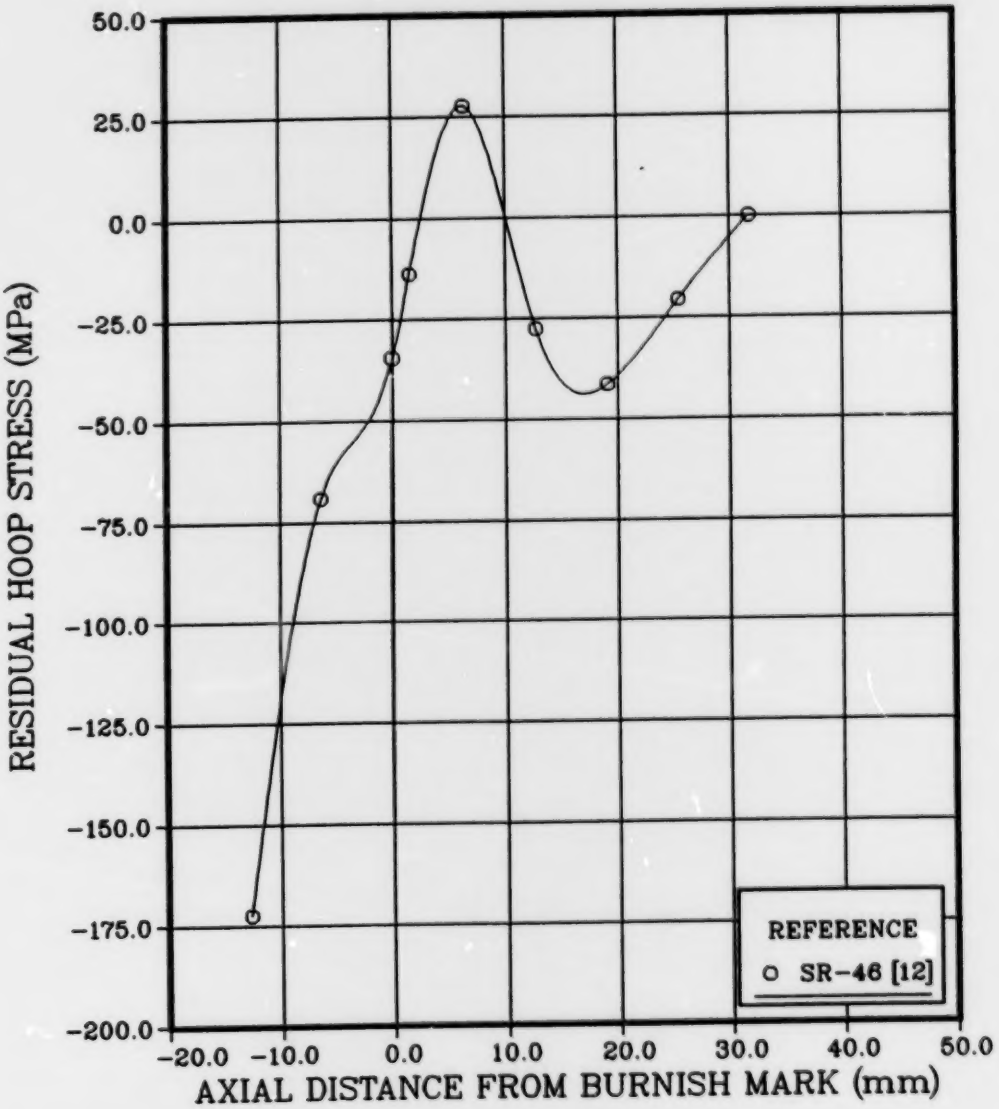

FIGURE 6.14 - Residual Hoop Stress Distribution Along the Outside Surface for Normal Clearance, Stress Relieved Rolled Joints

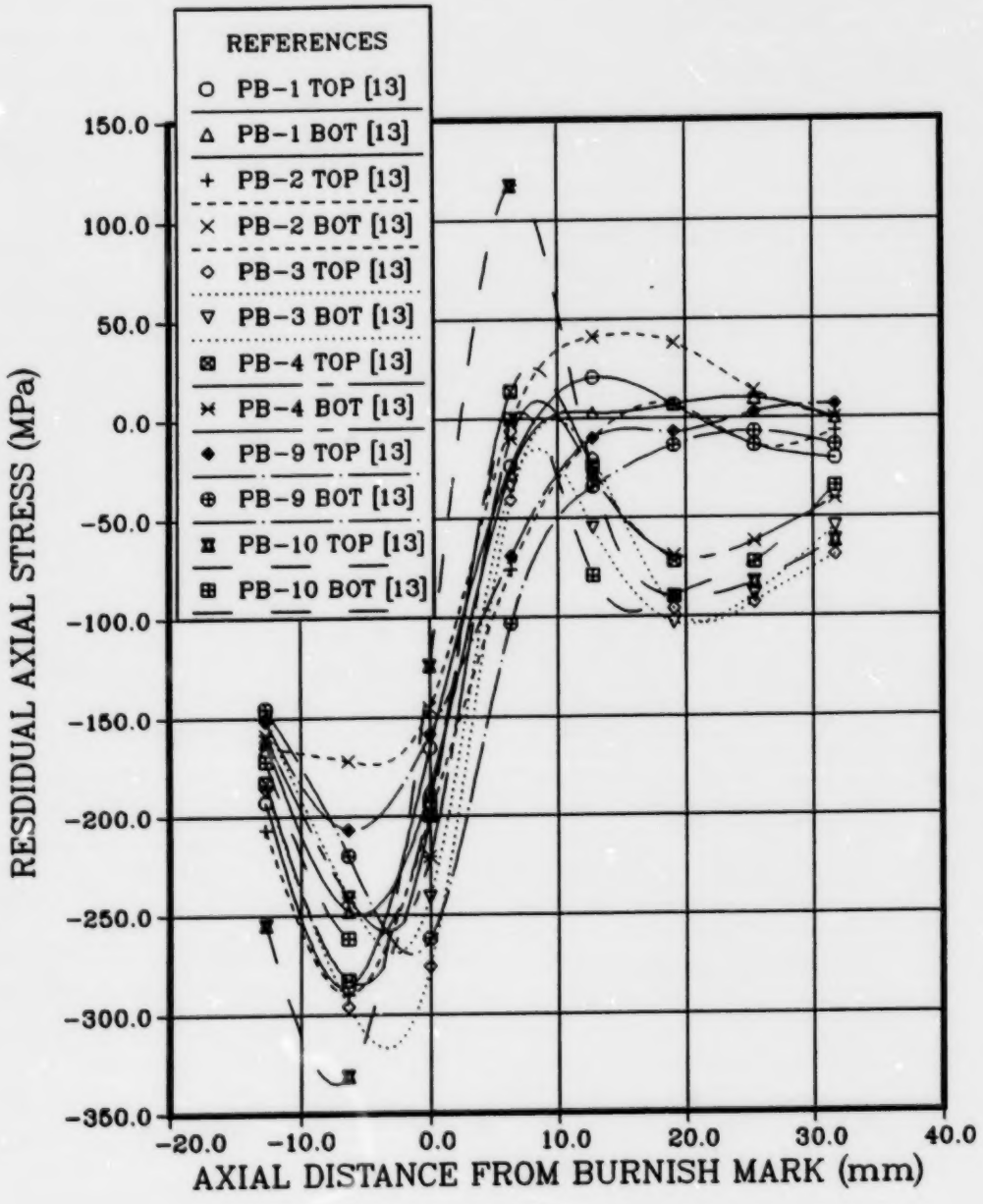

FIGURE 6.15 - Residual Axial Stress Distribution Along the Inside Surface for Zero Clearance Rolled Joints

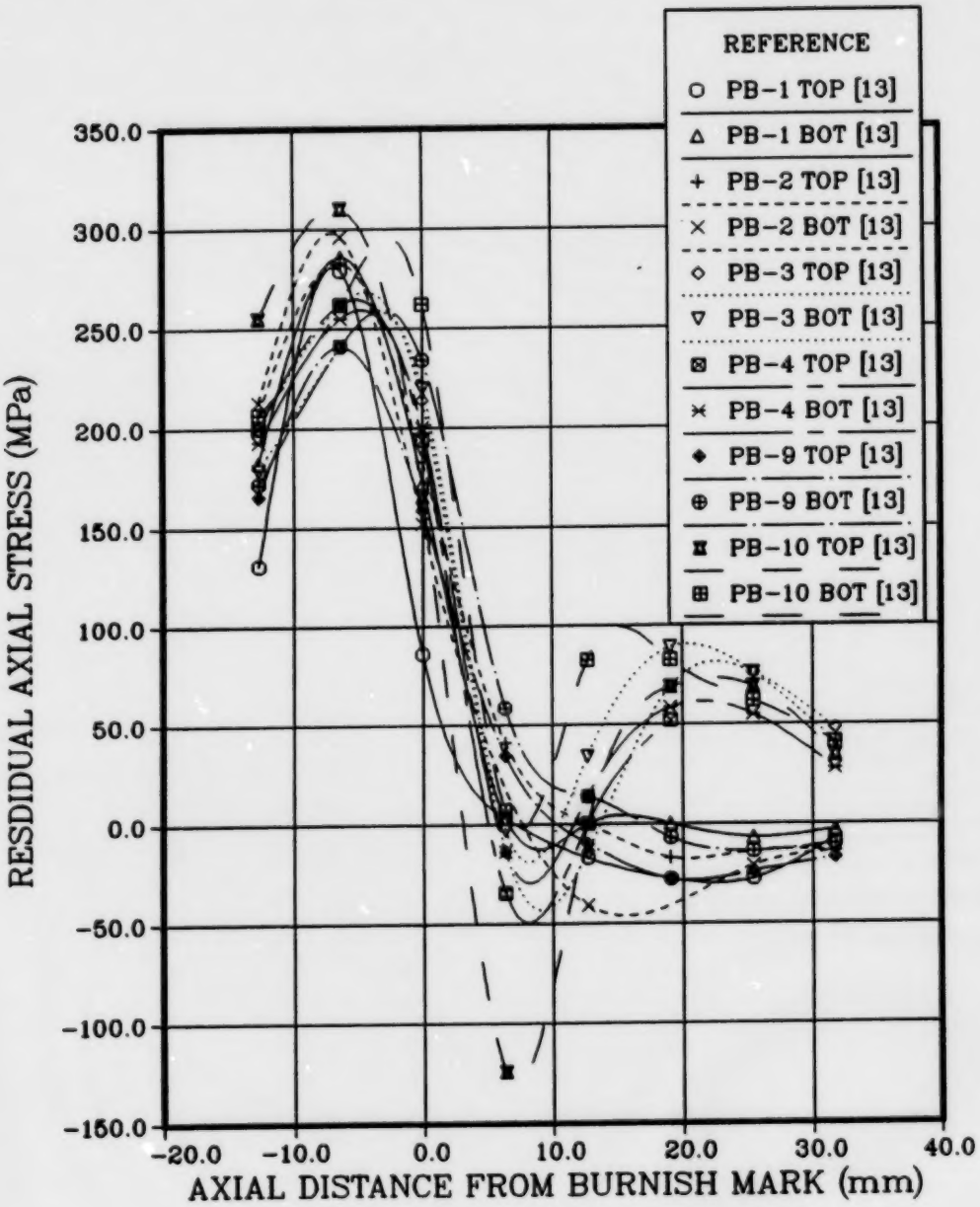

FIGURE 6.16 - Residual Axial Stress Distribution Along the Outside Surface for Zero Clearance Rolled Joints

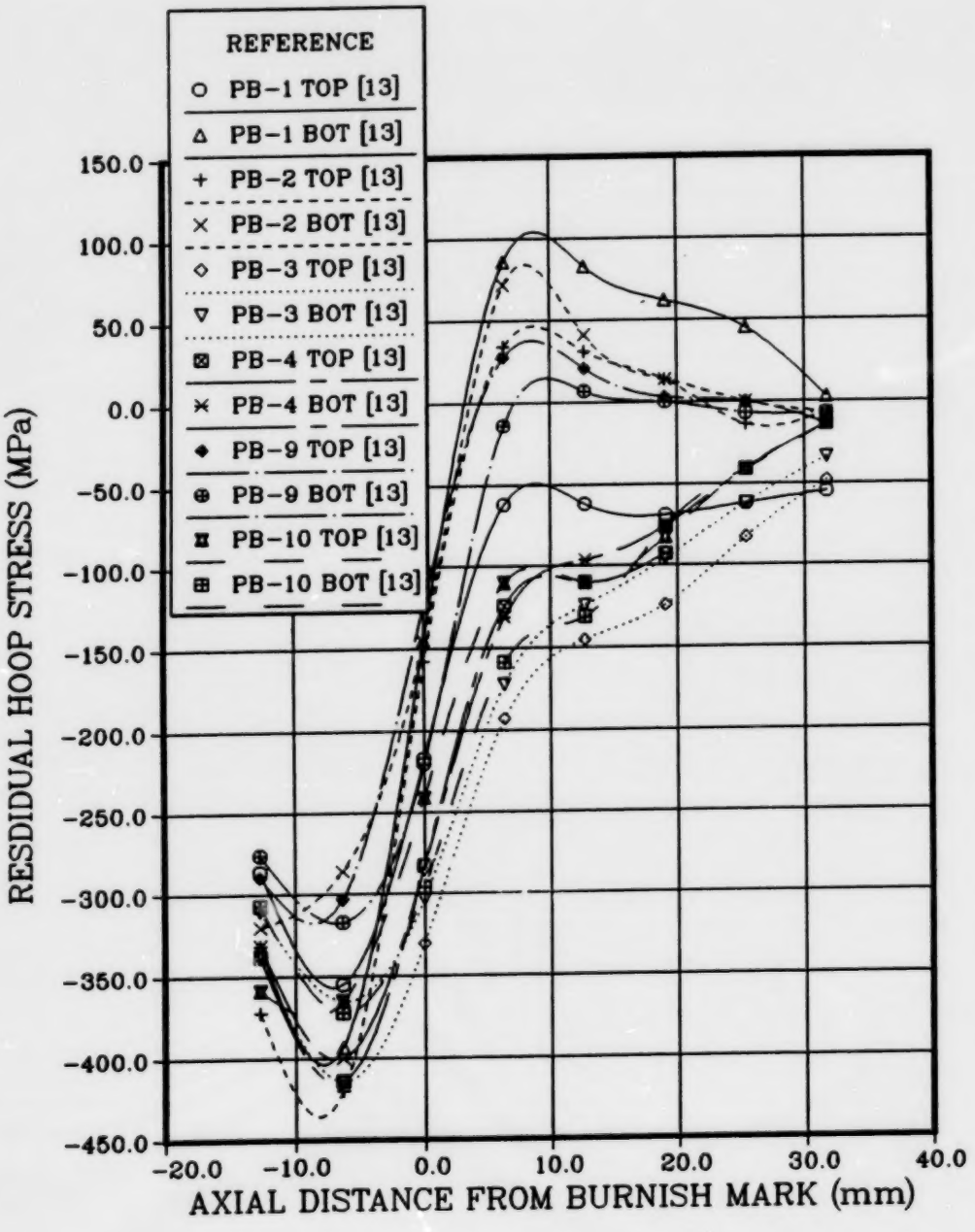

FIGURE 6.17 - Residual Hoop Stress Distribution Along the Inside Surface for Zero Clearance Rolled Joints

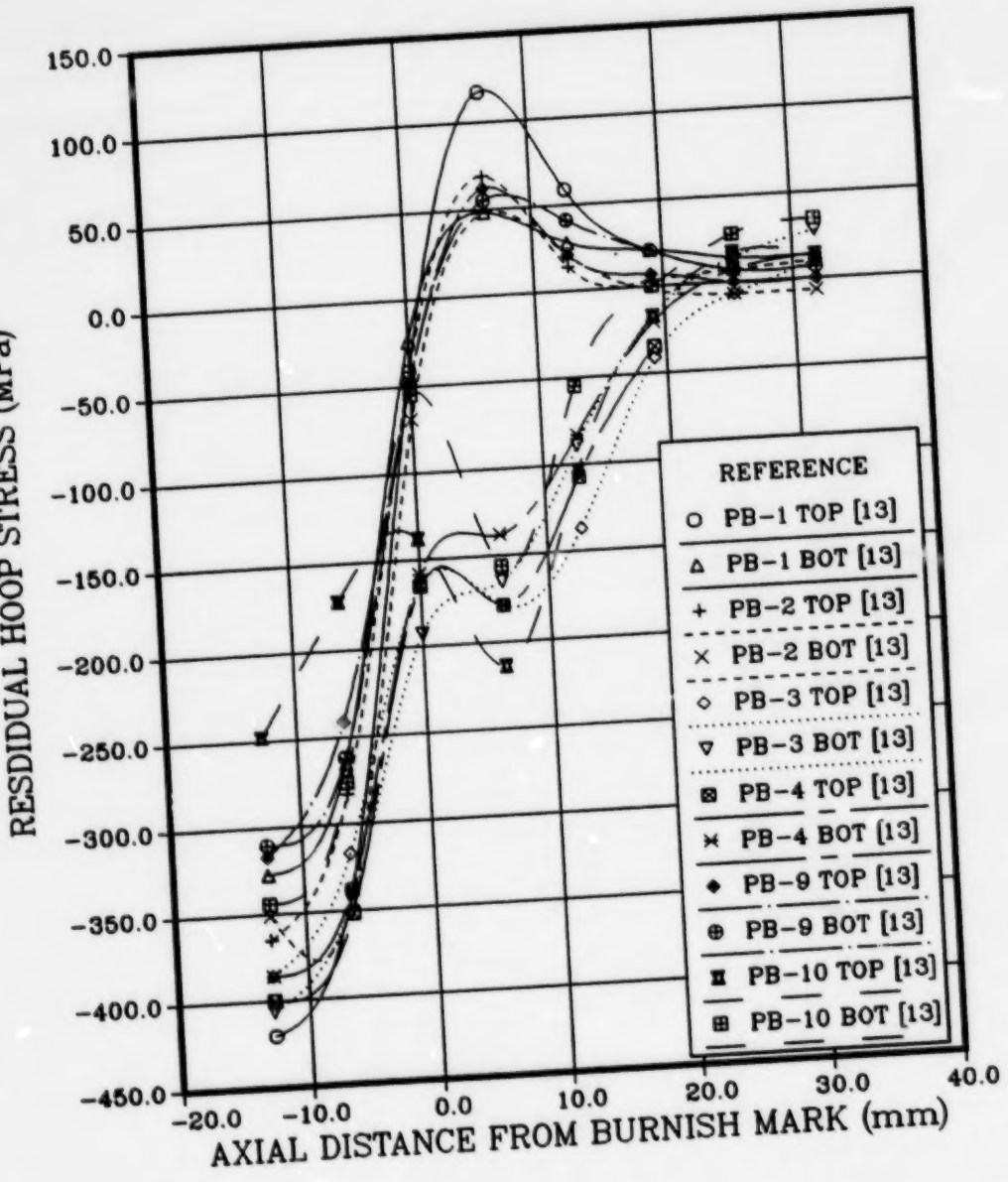

FIGURE 6.18 - Residual Hoop Stress Distribution Along the Outside Surface for Zero Clearance Rolled Joints

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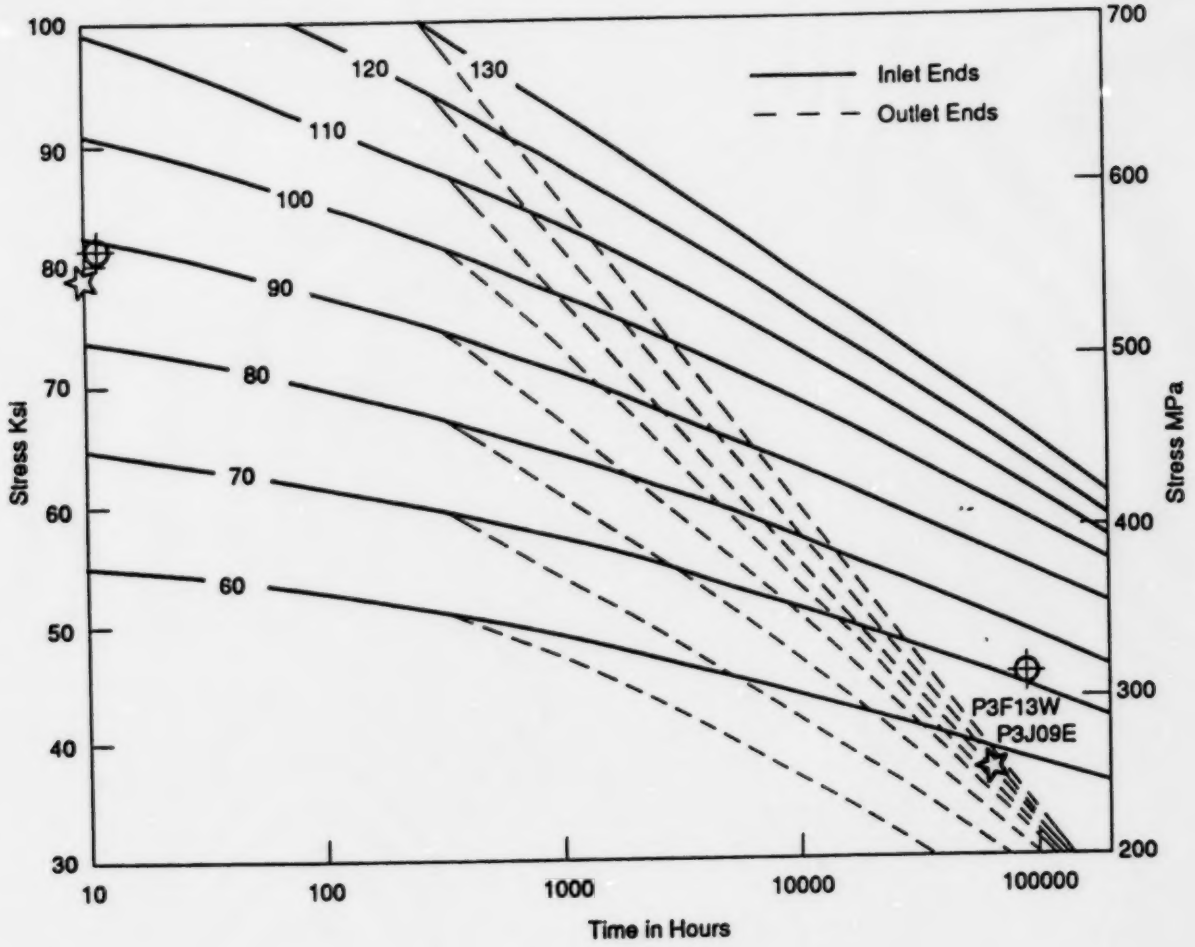

FIGURE 6.19 - Stress Relaxation Predictions Under Normal CANDU Operating Conditions

7.0 DISCUSSION

7.1 Parameters Controlling Residual Stress Magnitude

Because the rolling process has many complexities, the residual stress distributions can vary significantly. The effects of these complexities are reflected in the circumferential variations within one rolled joint/17/; in the measurement scatters for different rolled joints of the same type; and in the variations between different types of rolled joints. There are three main parameters that control the residual stress distributions in the rolled joint region. The first parameter is the amount of over extension by the tube-expander during rolling. If the tube-expander over-extended beyond the start of the end fitting hub taper, the rolled joint transition region of the pressure tube is unsupported and the diameter of the pressure tube over-expands. Thus, high residual stresses are resulted in both axial and hoop direction. The highest residual hoop stress is usually located just inboard of the burnish mark. In the installation of pressure tube, one of the end fitting assembly is rolled at the reactor site, while the other end is rolled at the manufacturing facility. Due to rolling difficulties, the end that was rolled at the reactor site was usually more over-extended. Thus, the residual stress level is higher and extends further inboard into the pressure tube than the other end.

The second parameter is the diametral clearance between the pressure tube and the end fitting hub before rolling. The magnitude of the residual hoop stress in the pressure tube depends on the amount of diametral expansion resulting from the rolling operation. If the diametral clearance is small or negative (interference fit), expansion of the pressure tube diameter in the rolled joint region will be minimal and will have low residual hoop stress. The axial residual stress, however, is not affected.

The third parameter is stress relieving. If a rolled joint is stress relieved after rolling, the residual stress distributions from rolling will be altered completely. The magnitude of the residual stress will largely depend on the stress relieving operation.

Other minor parameters that could affect the residual stress magnitude include the mechanical properties of the pressure tube and the end fitting, the rolling procedure and the wall thickness and ovality of the pressure tube.

Based on the above reasons, the fuel channels with the over-extended, normal clearance, non-stress relieved rolled joints should have the highest residual stresses. This is followed by the fuel channels with low clearance rolled joints.

7.2 Use of Residual Stress Distributions

The rolling process induces very localized residual stresses in the pressure tube. The residual stresses usually diminish to zero within 30 to 40 mm inboard from the burnish mark. If a flaw is located in this region, the residual stress resulted from rolling should be considered in the flaw evaluation procedure. The residual

stress distributions presented in Section 6 of this report can be used.

If the residual stress distribution for removed pressure tubes, which account for stress relaxation from service condition, are available, these could be used in the flaw evaluation of existing fuel channels of the same rolled joint type. Otherwise, the beginning of life (0 EFPH) residual stress distributions should be used as the first approximation. If a more detailed analysis if required, the stress relaxation model proposed by AECL (Section 6.7) could be used to predict the current residual stress level.

If the presented data (Figures 6.1 to 6.18) are to be used in a flaw evaluation, to be conservative, a measurement error of ± 35 MPa/6/ should be added.

7.3 Current Research Program

A number of research programs are being carried out under COG WP 22-WPIR #6412/18/. Experimental measurements and numerical simulations are being conducted at AECL-CRNL. The Mechanical Research Department is preparing a theoretical model to predict the rolled joint residual stress/19/. This model will be in the form of a computer program which uses the different rolling parameters as inputs for the prediction. The Mechanical Research Department will also be modelling the rolling process using a 3-dimensional finite element method. When these results are available, the data should be added to the current database.

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